Analysis of Radiosonde Humidity Errors Based on BOMEX Data

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Introduction

The carbon hygristor currently used in United States radiosondes has been found to yield incorrect humidities because the temperature of the hygristor and of the air passing through the hygristor duct differ from that of the ambient air as sensed by the outrigger thermistor.

The temperature difference stems mainly from heating of the black hygristor by solar radiation, by heat transfer from the sonde package, and from thermal lag of the hygristor as the sonde ascends (or descends in the case of the dropsonde) through the atmosphere with its temperature changes. The problem is further aggravated by the reduction in the rate of airflow through the hygristor duct of the radiosonde and a resultant reduction in heat transfer rate from hygristor to air, thereby increasing the thermal lag time. Also, thermal conditioning of the radiosonde before release apparently contributes to an initial hygristor temperature anomaly in the lowest 50 mb of the sounding.

Humidity errors resulting from the heating effect on the hygristor have been noted by Wallace and Chang (1969), Teweles (1970), Morrissey and Brousaides (1970), and Ostapoff, Shinners, and Augstein (1970). Bunker (1953), Mathews (1965), Morrissey and Brousaides (1970), and Harney (1971) have discussed the problems of thermal lag and ventilation. Teweles (1970) listed modifications to the duct that have been suggested in order to minimize the radiation errors and to reduce the thermal lag of the hygristor by increasing the ventilation rate. An improved duct has been designed and is planned to be in operational use by the latter part of 1971 or early 1972. The duct will be fabricated of material more opaque to solar radiation, will have a blackened interior, a substantial improvement in ventilation rate, and will have a separate duct channel beneath the hygristor duct to insulate it from the rest of the sonde package. It is expected that these modifications will substantially reduce the errors due to heating of the hygristor by solar radiation and by heat transfer from the sonde package. The error due to thermal lag of the hygristor will be substantially reduced by the improved ventilation, but will still exist.

The hygristor is an excellent sensor of the true humidity of an air sample. However, if the hygristor and the sensed air sample in its immediate vicinity have temperatures different from the ambient free-air temperature, the sensed relative humidity will not represent the humidity of the free air, but rather the humidity the ambient air would have if its temperature were changed to that of the hygristor. Thus, when the sensor relative humidity is related to the ambient air temperature as measured by the thermistor, the sensed and computed relative humidity will be too low if the hygristor temperature is higher than the ambient free-air temperature. The converse is also true.

In the case of the ascending radiosonde, three effects are quite noticeable: the effects of solar and package heating, the effect of thermal lag, and the effect of pre-release thermal conditions. The thermal lag, in response to decreasing temperature, causes the hygristor to yield both day and night humidity values that are too low. The solar effect, of course, is absent at night. The lag effect will approach zero in isothermal conditions and will reverse sign in inversions. Depending upon conditions before release, the sonde package may be either warmer or colder than the air temperature at release, causing humidity errors of either sign. This effect may manifest itself in an abrupt decrease of specific humidity from the surface value, based on psychrometric observations aboard ship, to the first point of the sounding, and unusually low humidities through the lowest 50 mb (approximate).

In the case of dropsondes, the hygristor is mounted on an outrigger and the resulting five- to ten-fold increase in its ventilation rate compared with that of the radiosonde substantially reduces the daytime solar radiation and package heating errors. The thermal lag effect will give an error of opposite sign to that given by the radiosonde. The net effects of the greater dropsonde ventilation rate (shorter lag time) and higher rate of change of temperature because of the dropsonde's fall speed tend to offset each other, however, and give a humidity error caused by lag that is of approximately the same magnitude as the radiosonde's. Thus, if simultaneous nighttime radiosonde and dropsonde soundings at the same location were available, these could be used to evaluate the lag corrections required for both instruments to bring the two humidity soundings into agreement.

Correction Procedure

Equiprobability Transformation -- Figure 1 schematically illustrates a procedure by which one set of biased measurements can be modified. The curves shown represent cumulative percent frequency distributions of specific humidity obtained during BOMEX from aircraft and radiosondes, nighttime and daytime, in the lowest 300 m of the soundings. These have been measured at the same position in time and space. The best set, the aircraft data, is considered the master set.

If we are interested only in averages, then the modifying procedure would be to change the 50th percentile values of the radiosonde distributions to the 50th percentile value of the aircraft data. Thus, a 14.0 g/kg value for the night radiosonde distribution and the 16.6 g/kg value for the day radiosonde distribution would be increased to about 17.8 g/kg for the aircraft distribution. In figure 1, the arrows at (a) of the 50th percentile from

14.0 g/kg upward and then horizontally to the "A curve and then downward illustrate this.

If we wish to modify an individual reading, we can use the following technique. Let us suppose, for example, that a 13.6 g/kg reading is obtained from the day radiosonde (RD) sounding. We then proceed upward from 13.6 g/kg to the radiosonde day curve. The intersection occurs at about 0.33 on the cumulative percent frequency curve. We then go to the same cumulative percen frequency on the aircraft curve, and from this intersection proceed downward to the abscissa at 17.6 g/kg. The daytime curve can be modified to the nighttime curve value at 16.3 g/kg, or both can be modified to the 17.6-g/kg aircraft value.

The difference between the aircraft (A) and nighttime radiosonde (RN) distribution curves in figure 1 reflects the thermal lag effect. The difference between the radiosonde (RN) and day (RD) curves reflects the solar radiation effect and, possibly, thermal conditioning before release.

Lag Corrections -- From Middleton and Spilhaus (1953), the following approximation is derived:

$$(T_h - T_a)_2 = (T_h - T_a)_1 \, e^{-t/\lambda} - \beta\lambda \, (1 - e^{-t/\lambda}), \tag{1}$$

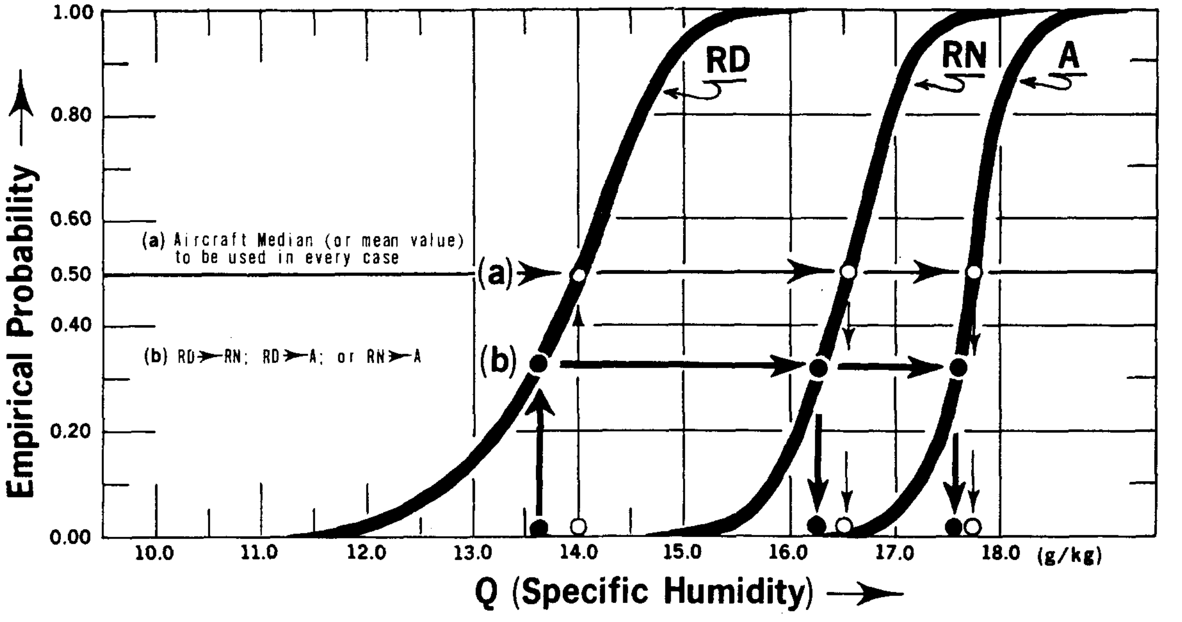

Figure 1. Schematic of proposed procedure for correction of BOMEX radiosonde humidity data. Curves represent actual cumulative frequency (empirical probability) distributions of specific humidity from daytime radiosonde (RD), nighttime radiosonde (RN), and aircraft measurements (A).

where T_h is the hygristor temperature in °C, T_a is the temperature of the ambient air in °C (as sensed by the thermistor), and t is the time in seconds since the previous point in the sounding. The time lapse rate term β equals $\Delta T_a/\Delta t$ and is assumed to be a constant between each pair of consecutive points. The lag constant in seconds is λ; subscripts 1 and 2 denote values at successive points in the sounding.

An initial approximation to the lag constant λ as determined by Glaser (Teweles, 1970) was considered to be about 30 sec, but it does vary with air density and ventilation rate. From lag constant calibration data for thermistors and application to BOMEX soundings, the following tentative relationship has been derived:

$$\lambda = 34.9(\rho V_v)^{-0.4} , \tag{2}$$

where ρ is the air density in kg/m^3 and V_v is the ventilation rate in meters per second.

The ventilation rate for the National Weather Service radiosonde has been determined by Ostapoff et al. (1970; see also Teweles, 1970) to be 28 to 33 percent of the ascent rate, i.e., approximately

$$V_v(R/S) = 0.3\ A, \tag{3a}$$

where A is the ascent rate in meters per second.

As noted earlier, the dropsonde hygristor was mounted on an outrigger arm directly in the airstream and ventilated at the fall velocity (approximately) 7.5 to 11.5 m/sec). Because the descent rates were not readily available for the BOMEX dropsondes, an approximate equation was derived from a small sample that gives the descent rate as a function of air density. Vertical air motions were ignored. The validity of this equation,

$$V_v(D/S) = 8.7\ \rho^{-0.6}, \tag{3b}$$

will be tested further with a larger sample and modified as required.

By substituting equations (3a) and (3b) into equation (2), we obtain the respective lag constants for the radiosonde, λ_R, and for the dropsonde, λ_D:

$$\lambda_R = 34.9\ (0.3\ \rho\ A)^{-0.4} \tag{4a}$$

$$= 56.5\ (\rho\ A)^{-0.4},$$

and

$$\lambda_D = 14.7\ \rho^{-0.16} \tag{4b}$$

The true ambient relative humidity at the ambient thermistor temperature, T_a, can be written

$$(RH)_a = \{e_s(T_h) / e_s(T_a)\} (RH)_i, \tag{5}$$

where $(RH)_i$ is the indicated relative humidity, and $e_s(T_h)$ and $e_s(T_a)$ are the saturation vapor pressures at the hygristor temperature and at ambient air temperature, respectively.

The above equations and their constants have been derived from the limited calibration data available, from a small set of data from BOMEX Period III (June 19 - July 2, 1969), and from results of previous work on this problem. They should therefore be considered preliminary and tentative, subject to change as this study progresses. Forthcoming BOMAP publications on this subject will be more specific and precise, and will contain supporting data from the literature as well as from BOMEX.

Pre-release Thermal Conditioning Errors -- Evidence exists that pre-release heating or cooling may cause humidity errors that affect the lower levels of the radiosonde soundings. Specifically, in some instances there appears to be heating from the ship's deck and superstructure; in others, cooling from the deck or from keeping the radiosonde in a cool room before release. This problem must be studied in more detail.

Solar Radiation Correction -- In order to evaluate the humidity error caused by solar heating of the hygristor and sonde package, we must first remove the errors due to thermal lag of the hygristor and to pre-release thermal conditioning. Evaluation of the magnitude of this error due to solar heating, and corrective procedures, will be covered in future reports.

Correction of Other Errors -- Effects other than those mentioned above are believed to be less significant and are given a lower priority for the present. These include heat generated by the sonde's battery and electronic components, entrainment of the heated wake of the balloon into the hygristor duct, variation of ventilation rate caused by the swinging of the sonde (Harney, 1971), wet-bulb effect of the thermistor when the sonde passes from cloud to dry warm air in and above the inversion, and pressure sensor errors due to drift and hysteresis. In addition, there are the residual instrumental errors inherent in the manufacturing process. These effects will be analyzed as time permits.

Results of the Lag Correction Procedures

The equations given in the preceding section have been used in modifying the BOMEX radiosonde and dropsonde humidity data shown in figures 2 through 4. Figure 2 shows the radiosonde, dropsonde, and aircraft data from and near the *Oceanographer* on June 26, 1969, during the night. Included are the radiosonde and dropsonde temperature data, identified as T_R and T_D, and specific humidity data, identified as R and D. The soundings are shown from about 1,020 mb (1.02 bar) to 750 mb (.75 bar). The abscissa scale is broken in order for both temperature and specific humidity data to be shown.

In figure 2, the radiosonde unmodified data are represented by the heavy broken line marked R, while the dropsonde unmodified data are identified by the dotted line marked D. The corrected humidity profiles are marked R_c and D_c, respectively. The aircraft data are shown at about 300, 1,300, and 2,300 m above sea level and are identified by solid circles and triangles. The circles indicate data obtained from a Cambridge Systems dew-point hygrometer; the triangles indicate data obtained from an infrared hygrometer. The times of observation for the radiosonde and dropsonde are, respectively, 0302 and 0235 GMT and for the aircraft 0212, 0242, 0554, and 0624 GMT. The aircraft was in the air more than 5 hours. The corrections to the curves are generally in the right direction, but at some levels there is an over-correction. The fact that the two soundings are removed in time and space by about ½ hour and 50 n mi may have some bearing on this.

Figure 3 illustrates another set of nighttime soundings, made on June 24, 1969. The ship is the *Discoverer* in the southeast corner of the BOMEX array. Here the corrected humidity profiles show good agreement only below 960 mb and near 850 mb, beneath the inversion. The difference in the corrected curves between these two levels may be the result of insufficient corrections, or may represent true differences over the 50-n-mi separation between the two soundings. The aircraft data in this case appear low, but they were

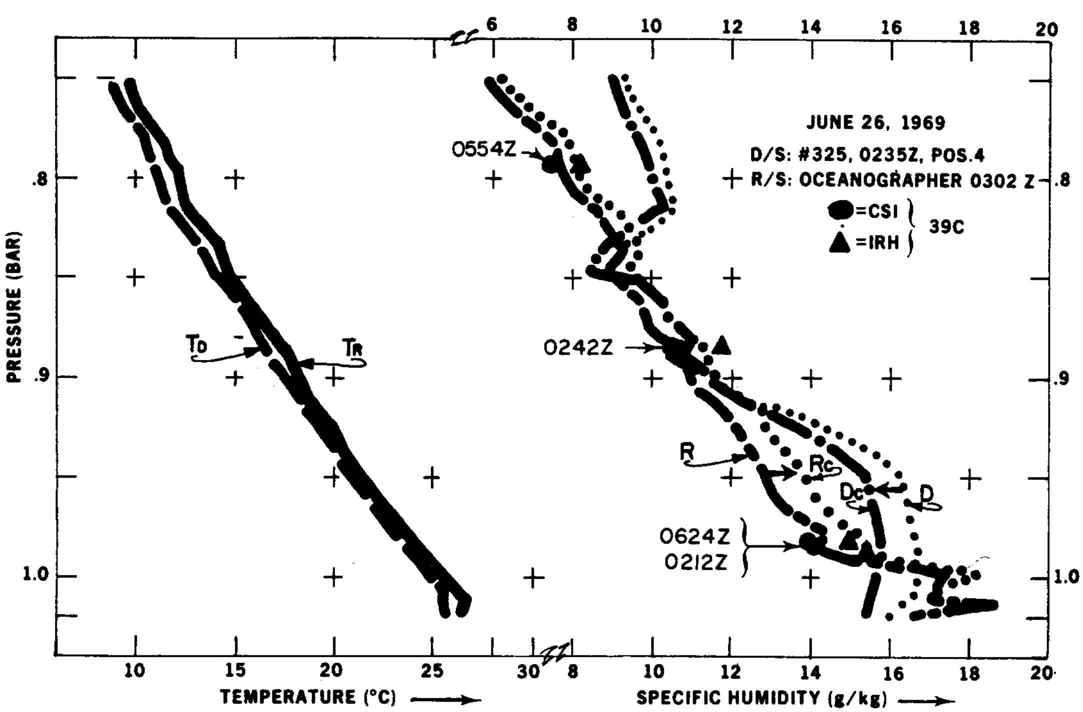

Figure 2. Radiosonde and dropsonde temperatures and specific humidities, before and after correction for thermal lag of hygristor, compared with aircraft-measured specific humidity. Nighttime soundings, June 26, 1969.

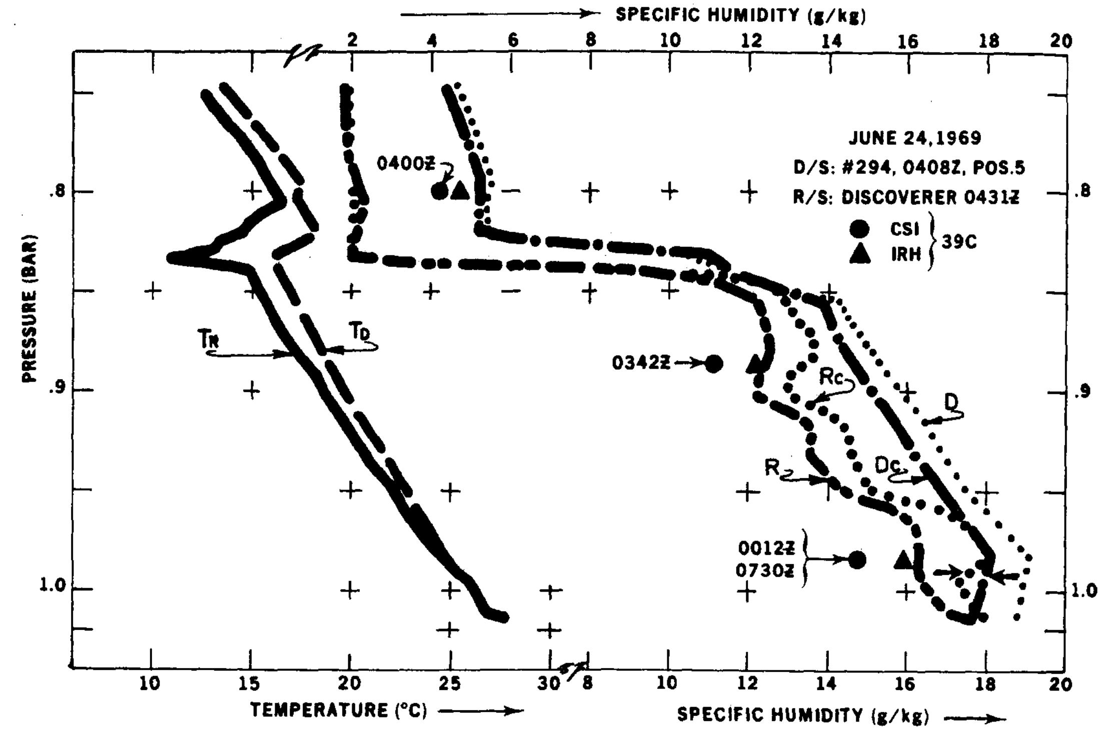

Figure 3. Same as fig. 2, for nighttime soundings, June 24, 1969.

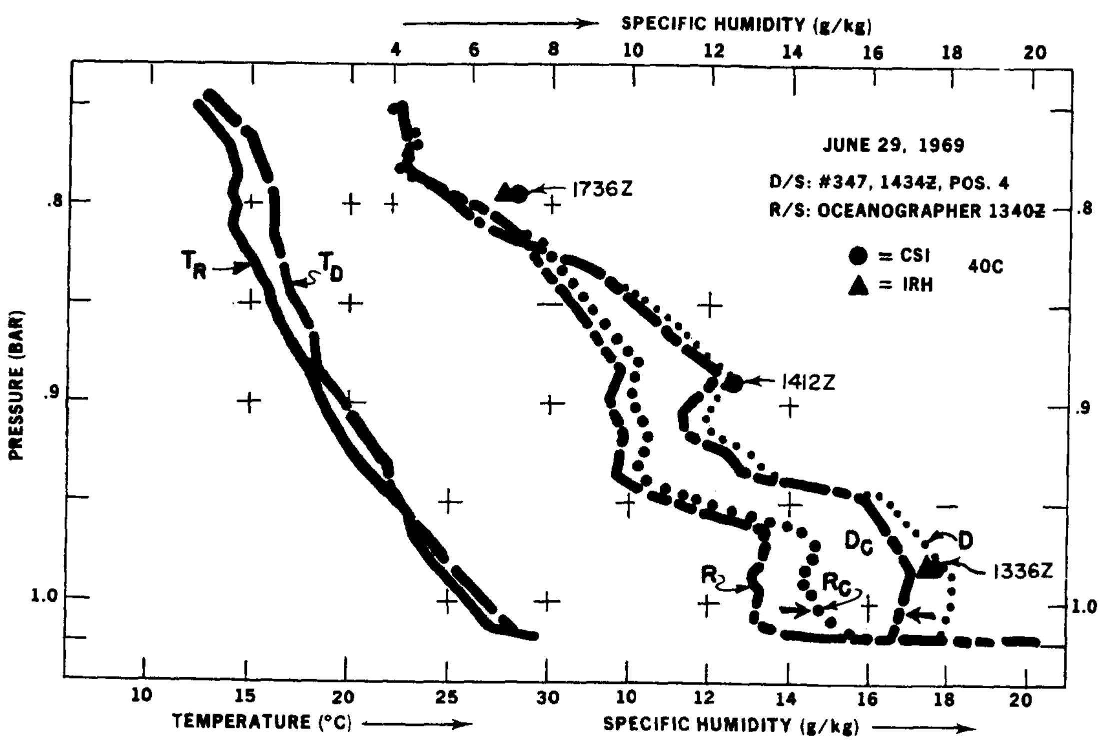

Figure 4. Same as fig. 2, for daytime soundings, June 29, 1969.

obtained from the DC-6 39C aircraft of NOAA's Research Flight Facility (RFF) and are known to be less reliable than data from the RFF DC-6 40C. The anomaly in the radiosonde temperature curve near 840 mb is presumably created by (a) evaporative cooling at the top of clouds and/or (b) the "wet-bulb effect" resulting from evaporation of moisture collected on the thermistor during ascent through the clouds.

The daytime pair of soundings in figure 4 perhaps better illustrates the modifying procedure. The soundings were made at and near the *Oceanographer* on June 29, 1969. Here, the sounding modification requires further correction. This, obviously, is the correction required for the solar heating effect on the radiosonde hygristor. Also, apparent heating effects from the ship's deck and superstructure are seen in both the radiosonde temperature and humidity curves. The surface temperature and humidity readings are those from the shipboard sling psychrometer rather than from the radiosonde.

Summary

Radiosondes and dropsondes currently used in the United States yield incorrect humidities for several reasons. For the radiosonde these include the effects of solar radiation during the day, inadequate ventilation, and thermal lag in the hygristors. For the dropsonde, the error is due mainly to thermal lag.

Lag corrective procedures have been established, and tentative lag constants determined. Results appear to be satisfactory, but a second evaluation of the constants in the lag correction equations, based on a larger data sample, will be made before final modifications of the BOMEX soundings.

Other effects, such as those of solar radiation, package heating, and pre-release thermal conditioning, are being checked and will be covered in subsequent reports.

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